ARPA-E Power Technologies Workshop
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Bulk GaN Materials for Next Generation Power Electronics

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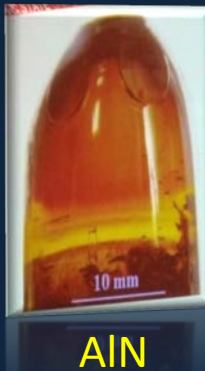
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- NRL (C. Eddy, K. Gaskill)
- SNL (A. Allerman)
- US Congress (David Price, 4th District NC)

Motivating Statements & Questions

Power Electronics Specialist
US Car Manufacturer

We will just buy GaN power switches from Japan

We always wait till DOD develops a new material device combination

US DOE Technologist

GaN will become very important!

Who will pay for bulk GaN's development?

WBGS Industry Guru

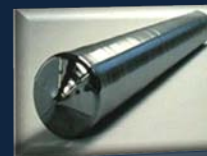Who will be the losers?

Who will be the winners?

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Market Challenge

400mm diameter

450mm diameter

300mm diameter

Si

200mm diameter

150mm diameter

Al$_2$O$_3$

Ge
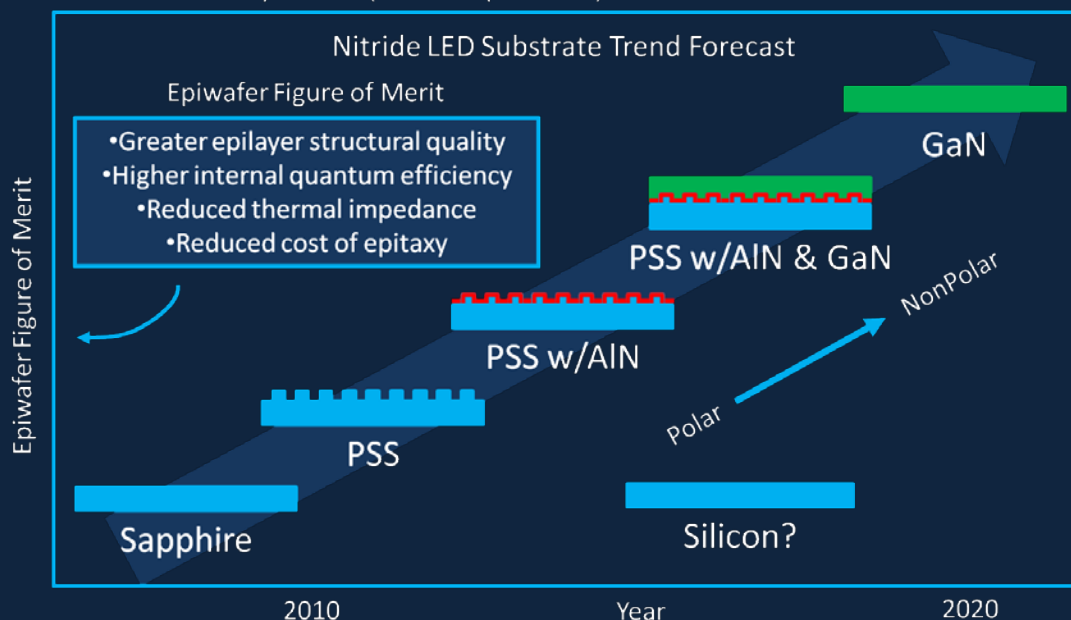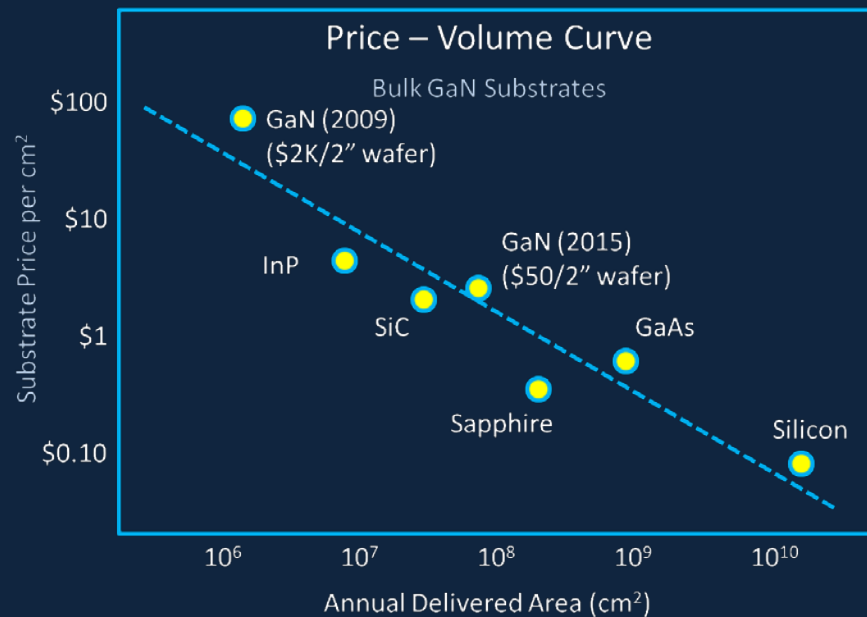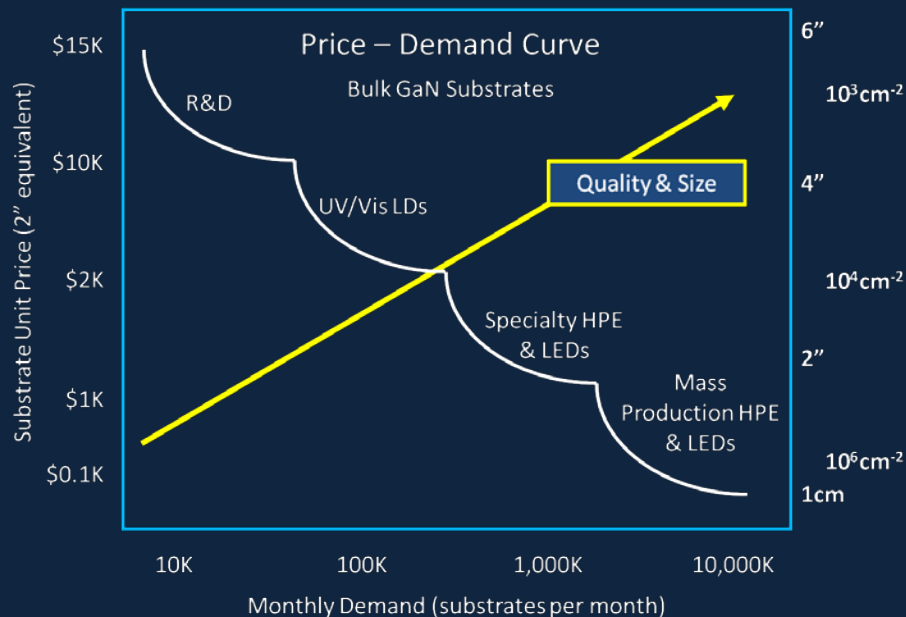
InP

GaAs

100mm diameter

SiC

25mm diameter

50mm diameter

AlN

GaN

Thermodynamic & Kinetic Ease, Volume Experience, Size, Crystalline Quality

Early US DOD investment in bulk SiC, InP, and GaAs has enabled many defense and commercial benefits

Price – Demand Curve

Bulk GaN Substrates

- R&D
- UV/Vis LDs
- Quality & Size
- Specialty HPE & LEDs
- Mass Production HPE & LEDs

Substrate Unit Price (2" equivalent): $15K, $10K, $2K, $1K, $0.1K

6", 10^3cm^{-2}, 4", 10^4cm^{-2}, 2", 10^6cm^{-2}, 1cm

Monthly Demand (substrates per month): 10K, 100K, 1,000K, 10,000K

Price – Volume Curve

Bulk GaN Substrates

- GaN (2009) ($2K/2" wafer)
- InP
- SiC
- GaN (2015) ($50/2" wafer)
- GaAs
- Sapphire
- Silicon

Substrate Price per cm^2: $100, $10, $1, $0.10

Annual Delivered Area (cm^2): 10^6, 10^7, 10^8, 10^9, 10^{10}

Nitride LED Substrate Trend Forecast

Epiwafer Figure of Merit

- Greater epilayer structural quality
- Higher internal quantum efficiency
- Reduced thermal impedance
- Reduced cost of epitaxy

- GaN
- PSS w/AlN & GaN
- PSS w/AlN
- PSS
- Sapphire
- Silicon?
- NonPolar
- Polar

Epiwafer Figure of Merit

Year: 2010, 2020

- Major foreign interest in bulk & template GaN substrate technology

- Next generation HEV needs >10^6 bulk GaN substrates/year

Baliga's Figure of Merit (BFOM)
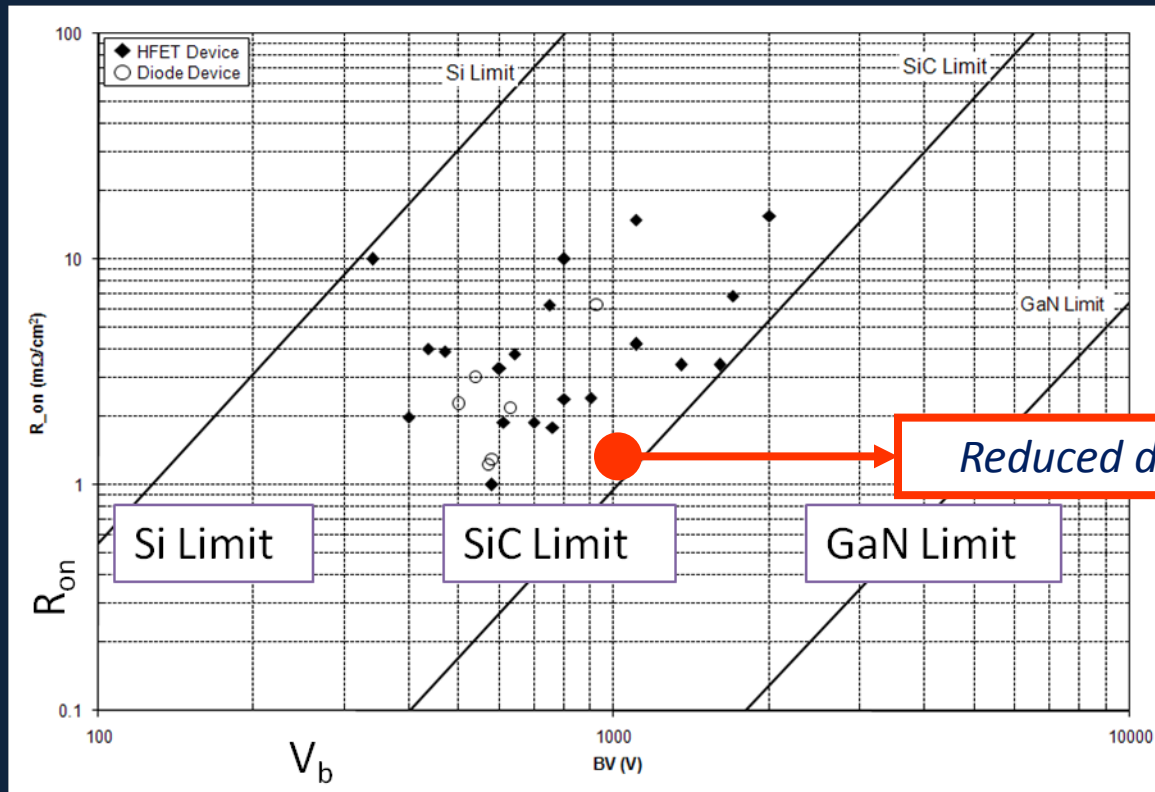
$$R_{ON} = \frac{4V_b^2}{\varepsilon_S \mu_n E_C^3}$$

$$BFOM = \varepsilon_S \mu_n E_C$$

Reduced defect density

- Considers on resistance & break down voltage

Figure of Merit	Expression
Combined (General)	$k_{th} \varepsilon \mu_e v_s E_c^2$
Keyes (Power Density & Speed)	$k_{th} [c\, v_s / (4\pi\varepsilon_s)]^{-1/2}$
Baliga FOM (Resistive Losses)	$\varepsilon \mu_e E_g^3$
Baliga High Frequency FOM (Switching Losses)	$\mu_e E_b^2$

ε_s is the static dielectric constant

μ is the mobility

E_g is the bandgap

V_g is the gate drive voltage

E_b is the breakdown field

R. W. Keyes, "Figure of Merit for Semiconductors for High Speed Switches," *Proc. IEEE*, vol. 60, pp. 225-232, 1972

B. J. Baliga, "Semiconductors for High-Voltage, Vertical Channel Field-Effect Transistors," *J.Appl.Phys.*, vol. 53, no. 3, pp. 1759-1764, 1982

B.J. Baliga, "Power semiconductor device figure of merit for high – frequency applications," *IEEE Electron Device Lett.*, vol. 10, pp. 455-457, 1989

T. Ayalew, "SiC Semiconductor Devices, Technology, Modeling, and Simulation," http://www.iue.tuwien.ac.at/phd/ayalew/node76.html

Factor	Si	SiC	GaN
Baliga Figure of Merit	1	223	868
Dislocation Density (cm^{-2})	< 1	10^3	10^4 -10^6
Micropipe Density (cm^{-2})	0	30	0
Stacking Fault Energy (mJ/m^2)	55	14.7	20
Crystalline Polytypes	1	>245	2
Diameter	12"	4"	2"

An additional advantage of GaN over Si and SiC is the ability to bandgap engineer via growth of epitaxial heterostructures
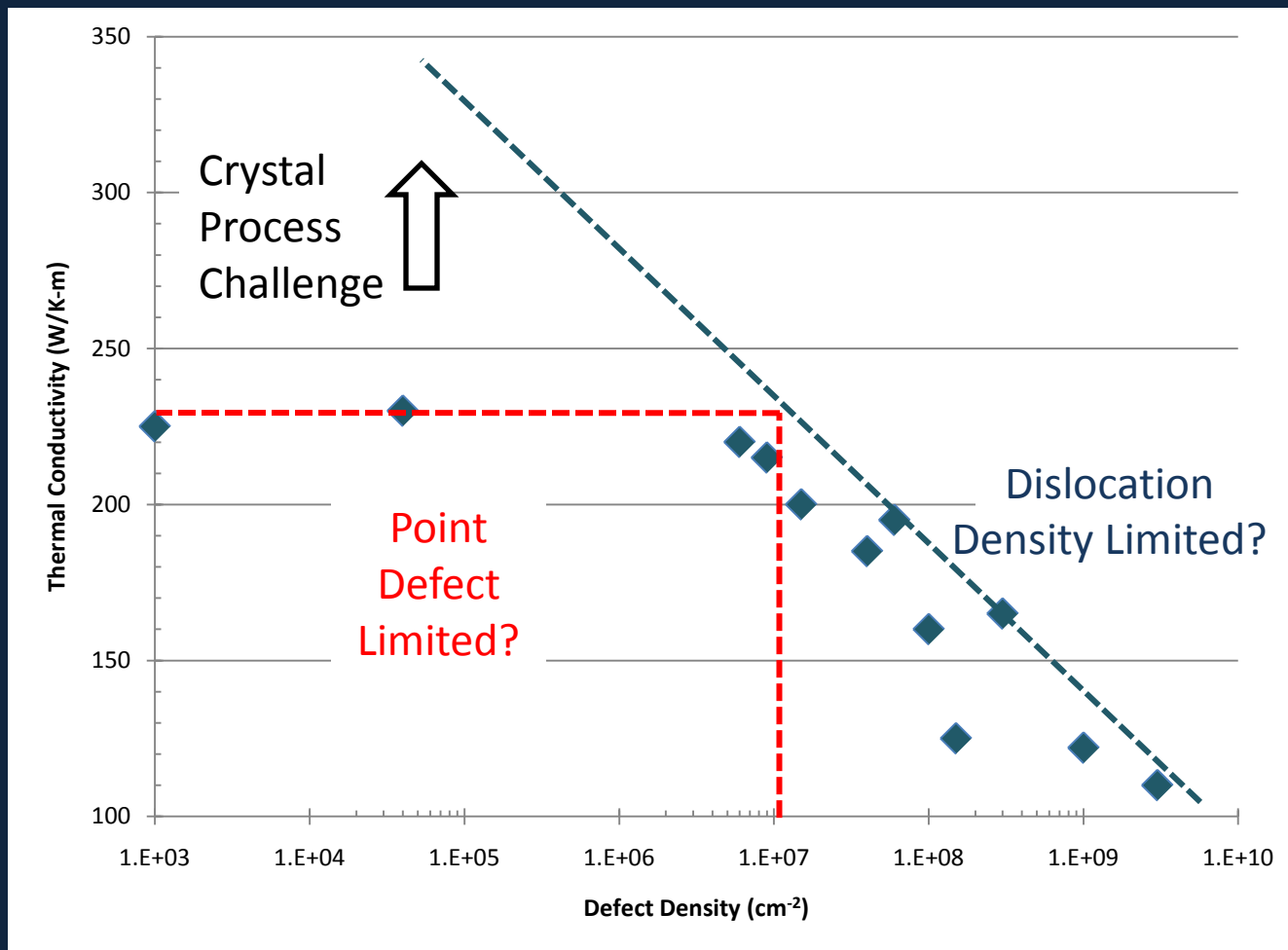
NCSU & Georgia Tech
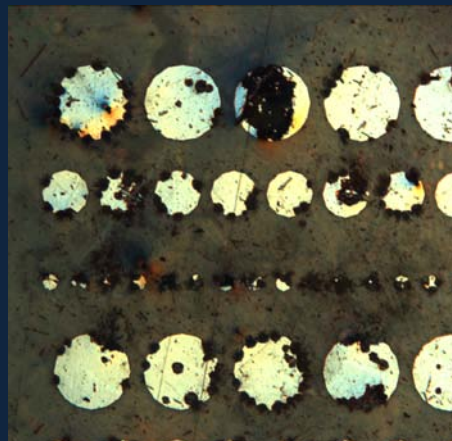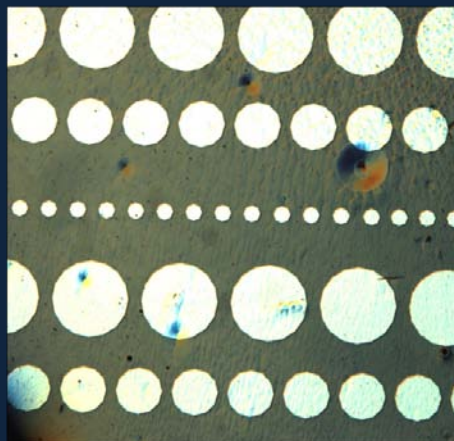
Thermal Conductivity vs. Dislocation Density
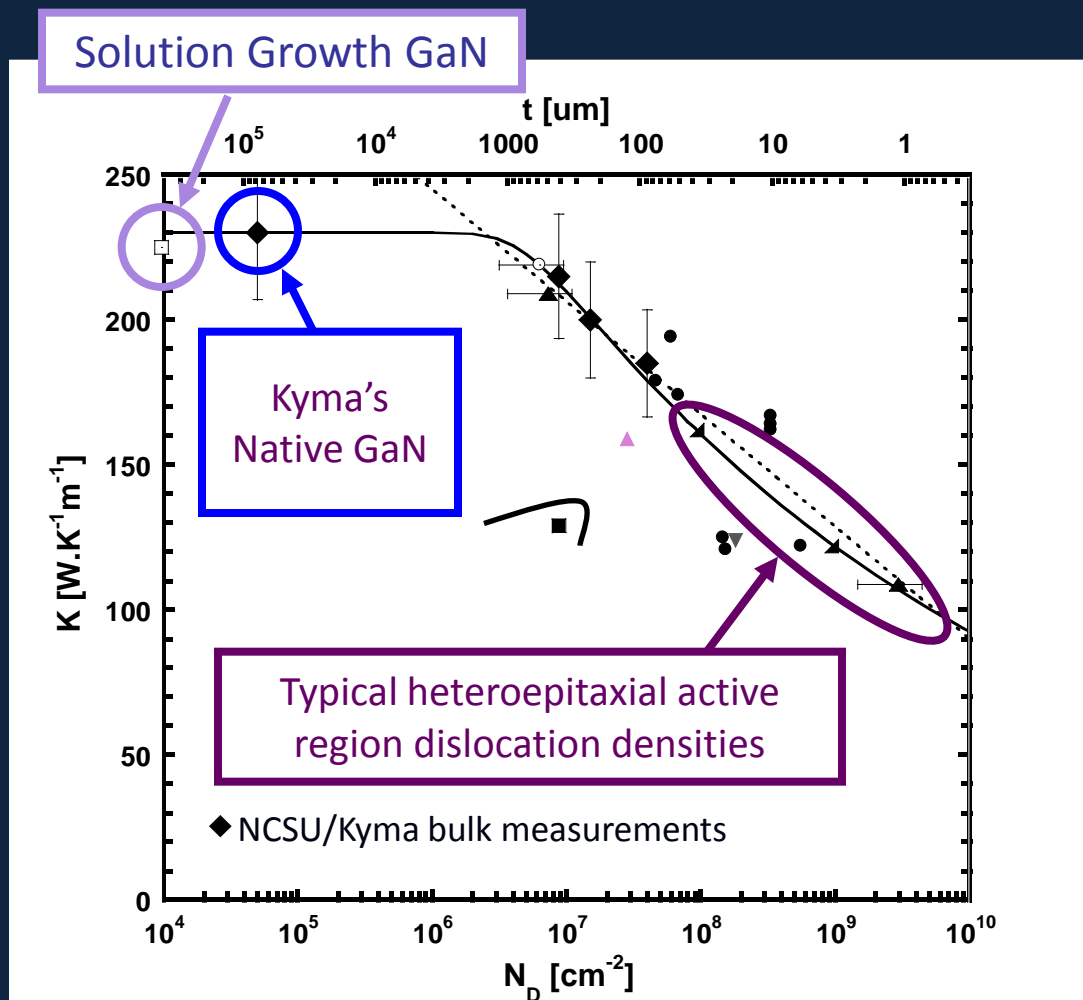
Accurate dependence of gallium nitride thermal conductivity on dislocation density, by C. Mion, et al., APL 89, 092123 2006.

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Thermal Conductivity vs. Dislocation Density

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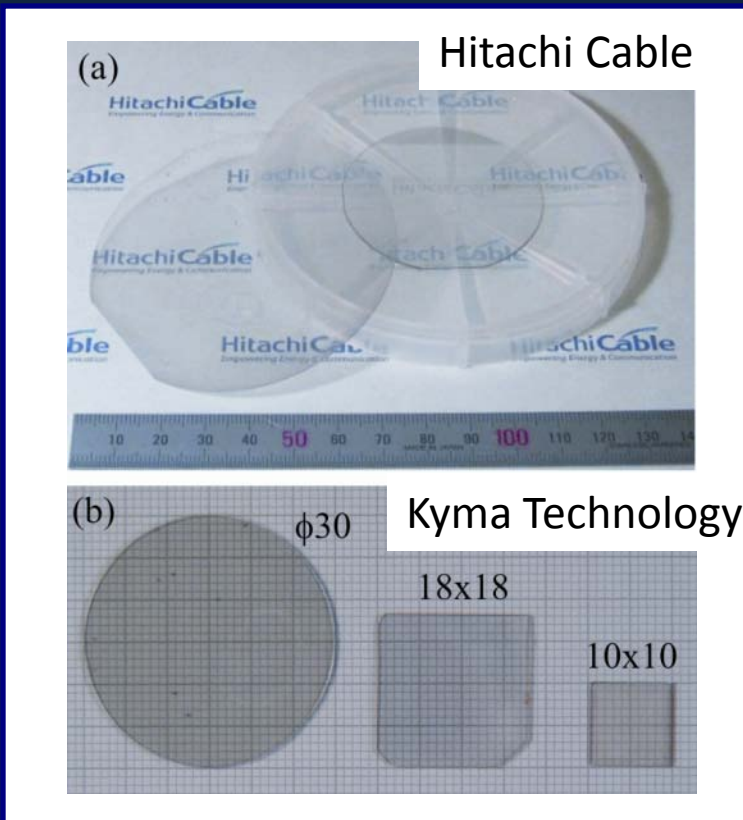
Un-passivated, simple Schottky diode demonstration, from collaboration with NCSU (Mark Johnson), Auburn University (Minseo Park), & Sandia National Laboratories (Andy Allerman)
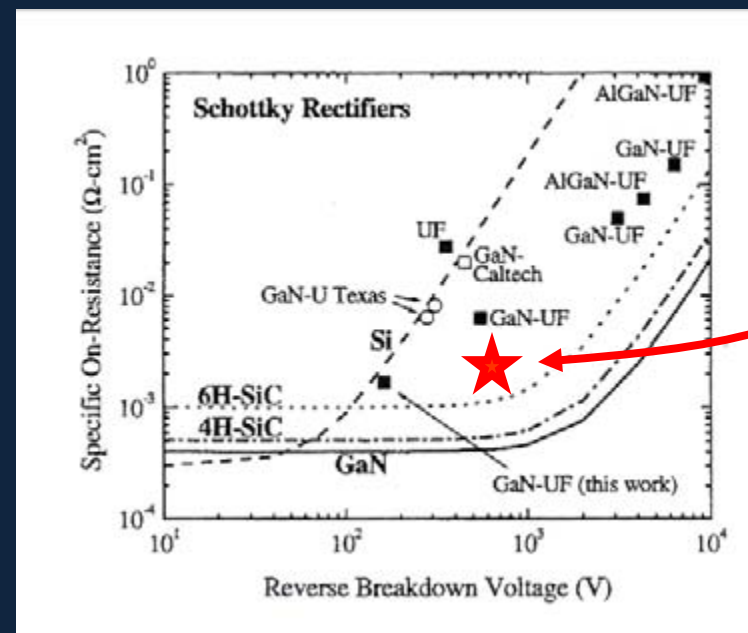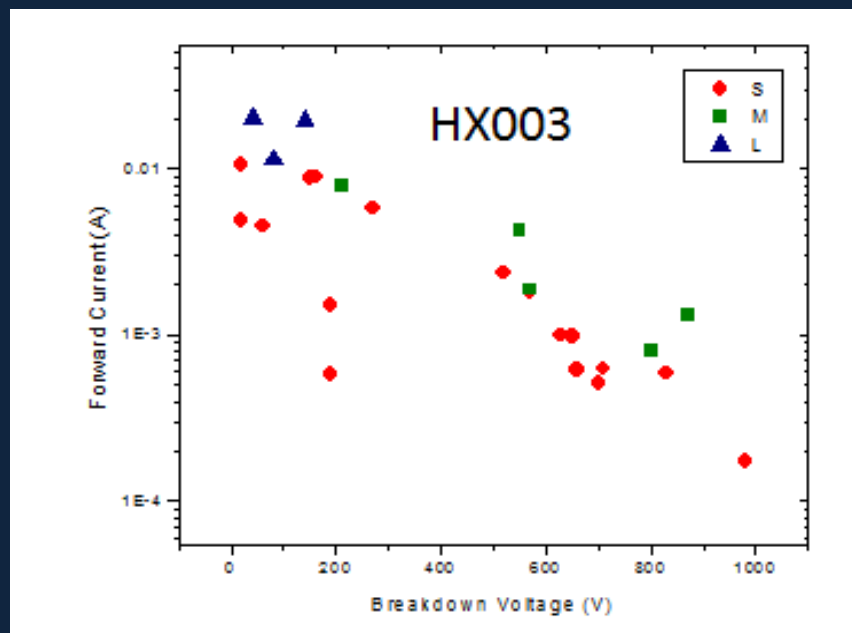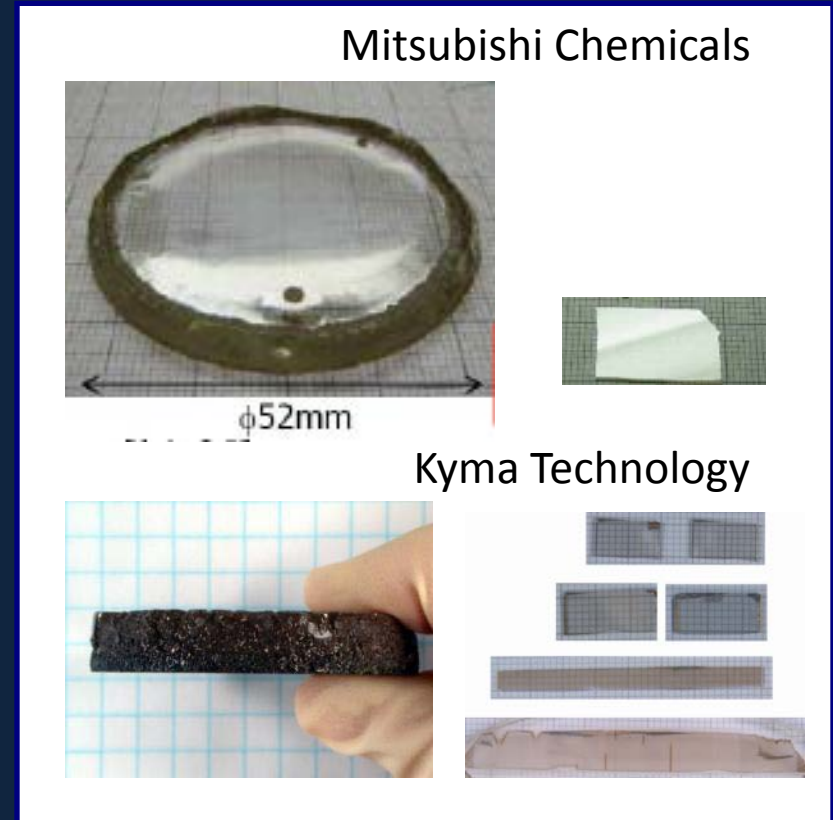

From: Johnson et al., IEEE Trans. Electron Dev., 49, 32 (2002).)
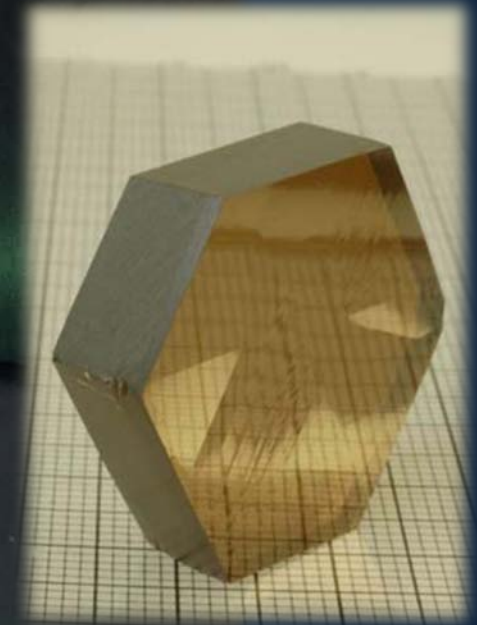
Native GaN Substrate Progress

- ## Single wafers

Hitachi Cable

Kyma Technology

- ## Boules

Mitsubishi Chemicals

Kyma Technology

WS-1 "Substrates for Nitride Epitaxy" IWN2008, Switzerland 2008

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0.5mm x 30mm GaN substrate
with TDD ~$1E^6cm^{-2}$

8mm x 25mm GaN
boule with TDD
~10^3cm^{-2}
R. Kucharski, et. al,
APL **95** (2009) 131119

Comparing Bulk GaN Crystal Growth Technologies

From Iza Grzegory's Poem Based on 6th International Workshop on Bulk Nitride Semiconductors

HVPE Bulk GaN

- They grow quite fast and thick
- However not too smooth
- One really needs a trick
- To make them really good
- It seems that what they need
- To grow in perfect way
- It's just a perfect seed
- Available some day

Ammonothermal Bulk GaN

- What does ammono show
- That crystals really grow
- Although the growth is slow
- They have not any bow

Source: *http://www.unipress.waw.pl/iwbns6/fun-concl.html*

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Comparing Bulk GaN Crystal Growth Approaches

Qualitative Feature vs. Growth Approach	HVPE	AMT	AMT on HVPE Seed	HVPE on AMT Seed
Growth Rate	👍👍👍	👍	👍	👍👍👍
Electrical Conductivity Control	👍👍👍	👍	👍	👍👍👍
Seed Generating Potential	👍👍	👍👍👍	👍👍	👍👍👍
Growth Parameters (P, T)	👍👍👍	👍	👍	👍👍👍
Time to Market	👍👍👍	👍	👍	👍👍👍
Substrate Quality	👍👍	👍👍👍	👍👍👍	👍👍👍
*Bulk GaN Process Figure of Merit (+)	21	11	9	24
*Bulk GaN Process Figure of Merit (x)	1536	12	6	4096

*FOM Calculation Assumes 👍👍👍👍 = 4, 👍👍👍 = 3, 👍👍 = 2, 👍 = 1

Summary & Conclusions

- GaN's importance will grow and grow
  - GaN is 2nd only to Silicon in importance
  - Bulk GaN will become cheap and readily available

- Unfettered access to bulk GaN will drive device and system innovation of unprecedented long term importance
  - The market will support only a few winners

- Major US investment in bulk GaN represents a great opportunity that cannot be overlooked